Three-dimensional Computational Modeling of Turbulent Flow Field, Bed Morphodynamics and Liquefaction Adjacent to Munitions

Project Number MR-2732

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In-Progress Review Meeting

May 15, 2018

SERDP
DOD ▪ EPA ▪ DOE

MR-2732: 3D Computational Modeling

Performers: Xiaofeng Liu (PI) and Tong Qiu (co-PI)

Technology Focus

- *To build 3D computer models for underwater munition response*

Research Objectives

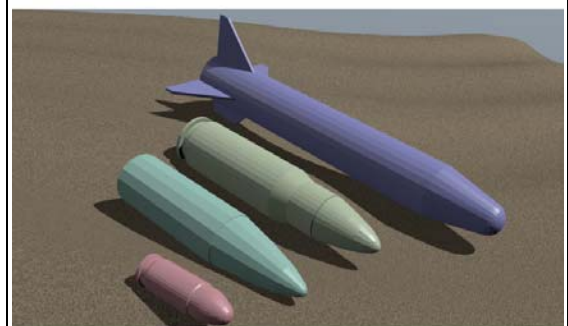
- *Develop and utilize computer models to identify and investigate the key control parameters of initiation of motion, transport, and burial/exposure of underwater munitions.*

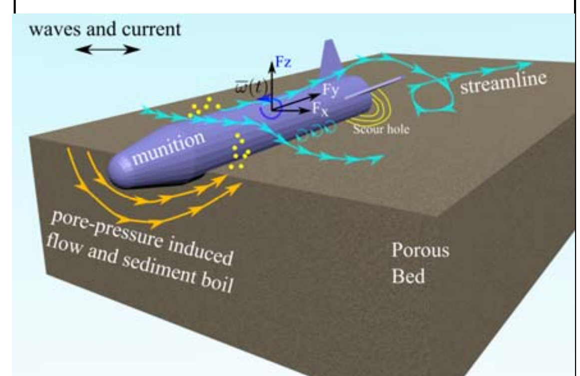
Project Progress and Results

- *Models are being developed (CFD model is done and SPH model is under development)*
- *Performed some preliminary simulations*

Technology Transition

- *At current stage, we work with other PIs to identify the needs in their projects, mainly how to complement laboratory and field measurements.*





Social Media Content

High performance computing for safer beaches: *researchers in the Civil and Environmental Department at the Pennsylvania State University are currently developing a comprehensive modeling framework to model the multiphysics processes governing the fate of unexploded munitions on the coastal areas.*

Project Team

Dr. Xiaofeng Liu

Pennsylvania State University

Specialist in computational fluid dynamics, sediment transport, erosion and scour

Dr. Tong Qiu

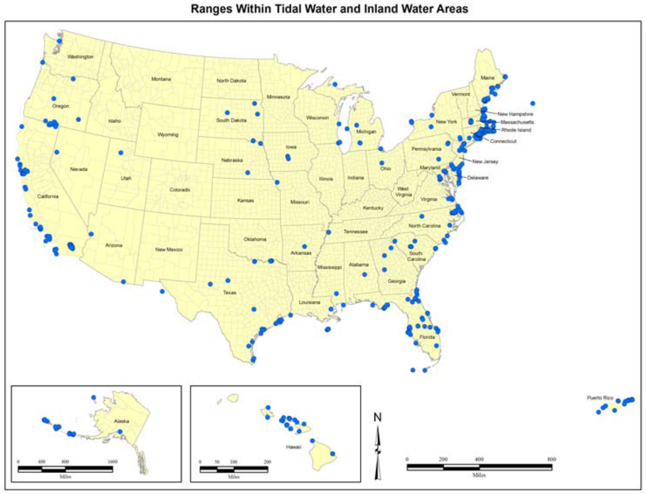
Pennsylvania State University

Specialist in computational geomechanics, soil mechanics, soil-structure interactions

Problem Statement

- DoD has identified more than 400 sites (> 10 million acres) potentially containing underwater munitions.
- The fate and transport of underwater munitions are important for risk-assessment and site remediation.
- Physical processes controlling the mobility and burial/exposure of munitions: turbulent flow, sediment transport, munition 6-DoF motion, and bed response
- Extensive field and laboratory investigations. However, high-fidelity computational modeling effort is lacking.

Ranges Within Tidal Water and Inland Water Areas



(SERDP/ESTCP White Paper, 2010)

Technical Objective

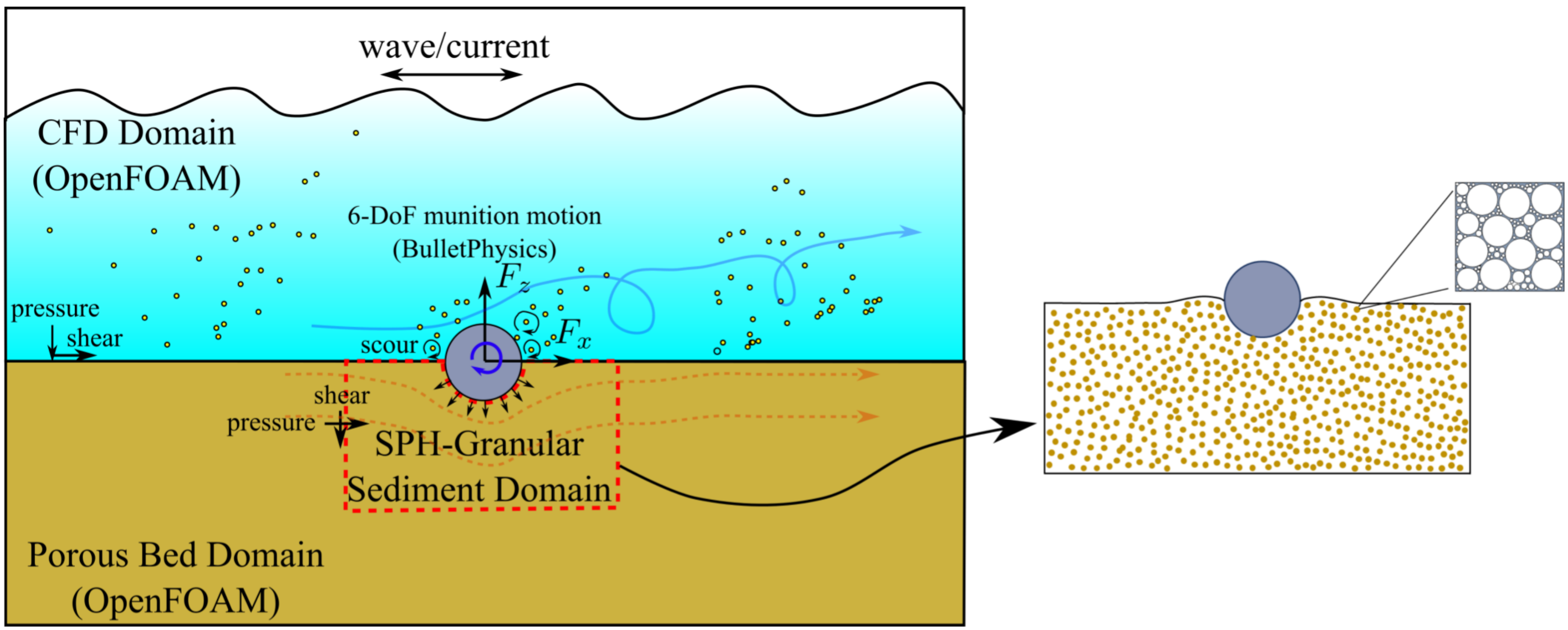
To build a 3D computer model to understand the mechanisms and identify key parameters of the initiation of motion, transport, and burial of underwater munitions.

Fundamental questions:

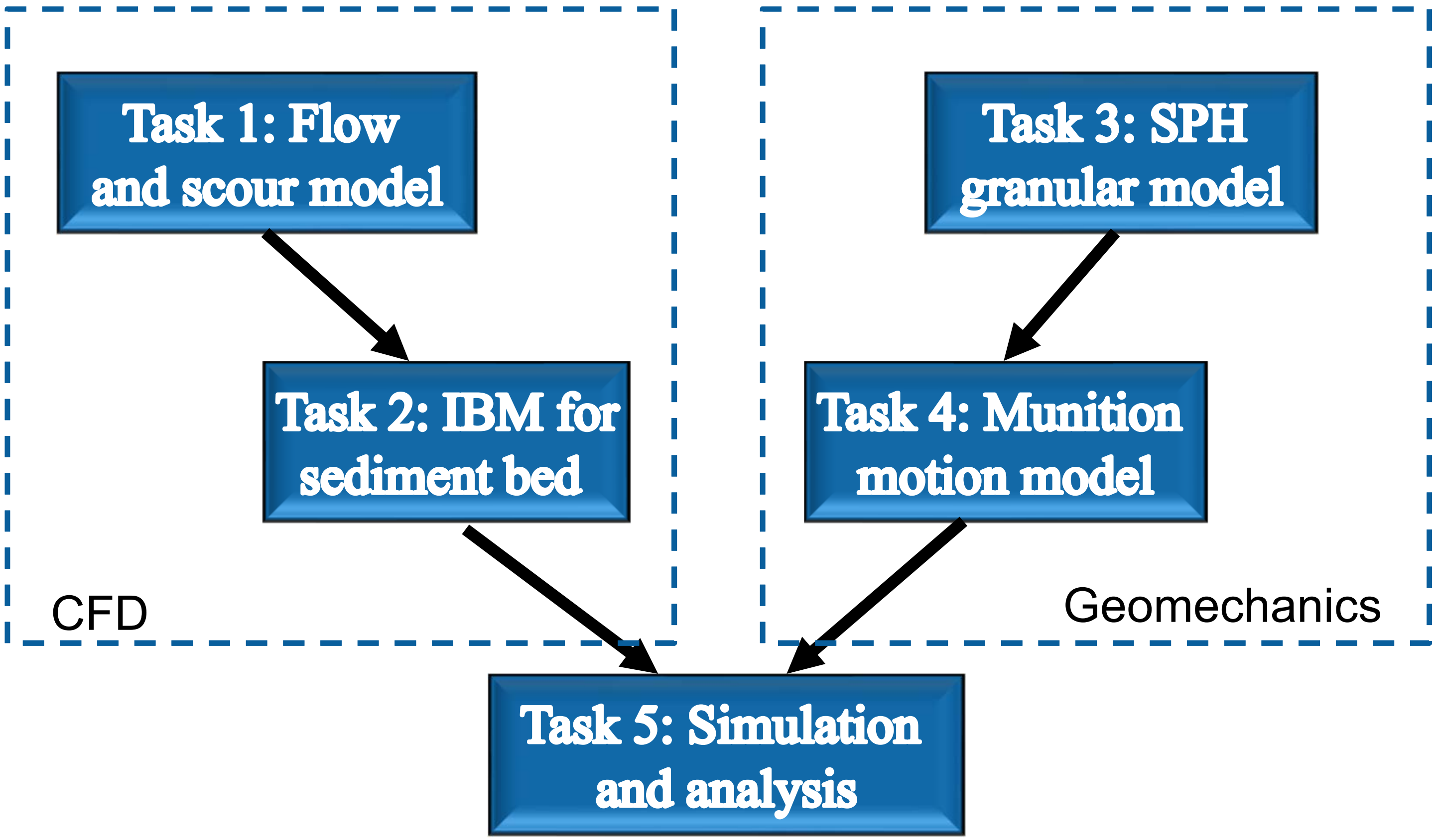
- ♦ How to describe the turbulent flow: the major driver of all physical processes?
- ♦ How to quantify the effects of munition density, size, geometric shapes?
- ♦ Are the empirical drag and lift force coefficients applicable to munition objects?
- ♦ What is the effect of liquefaction (excessive pore-pressure) on munition response?

Technical Approach

- To develop a comprehensive modeling framework coupling the sub-models for different processes
- To use the framework to simulate, analyze and synthesize



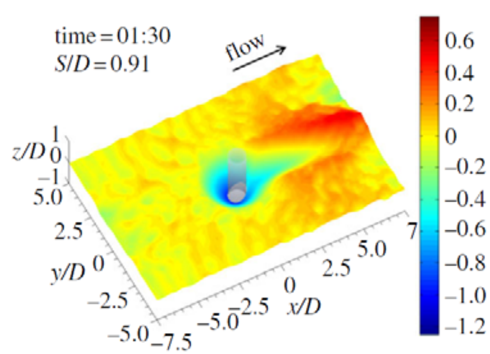
Technical Approach

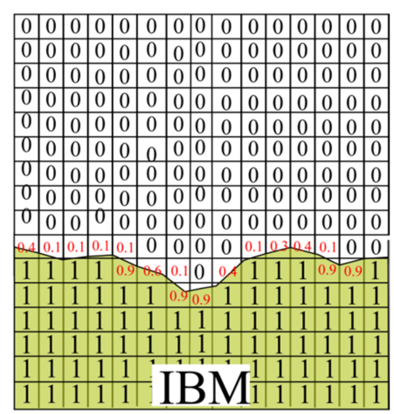


Technical Approach
Task 1 and 2: Flow and scour model/Immersed boundary method for sediment Bed

Objectives:

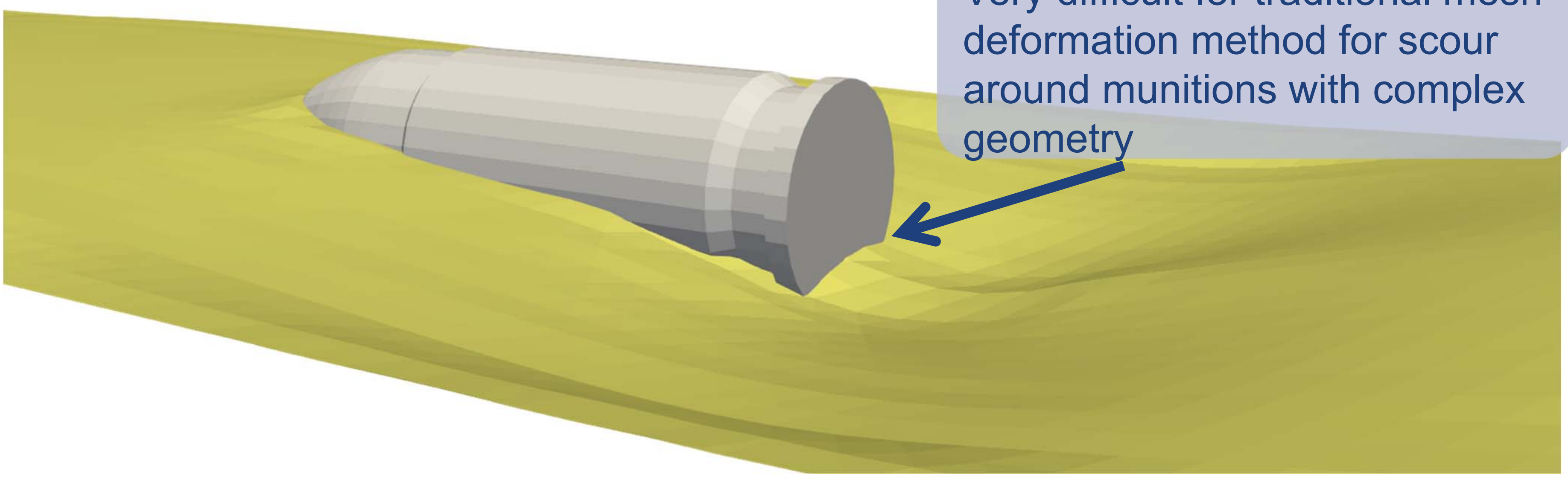
- Task 1: Modify, improve and test our existing turbulent flow solver and sediment transport model implemented in OpenFOAM.
- Task 2: To track the deforming sediment bed and moving munition more easily





Technical Approach

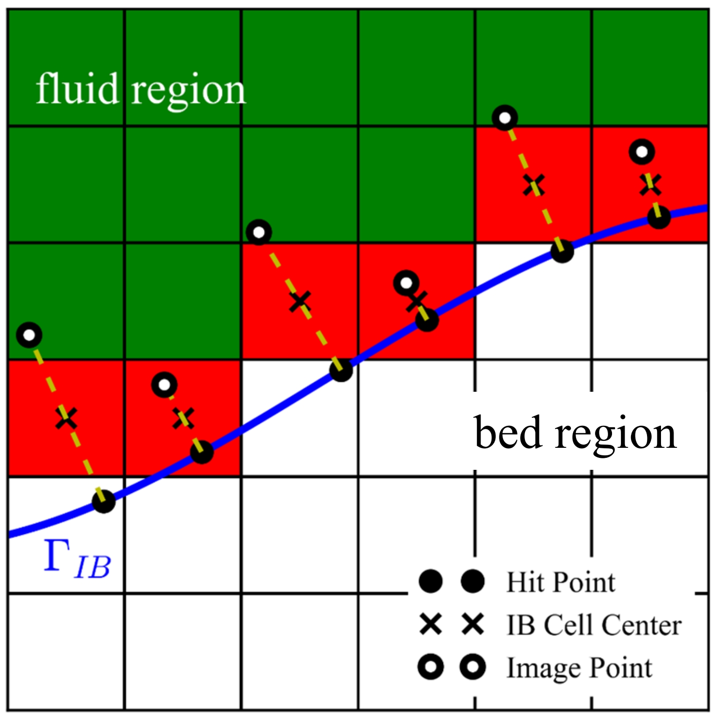
3D scour model + Immersed boundary method



Very difficult for traditional mesh deformation method for scour around munitions with complex geometry

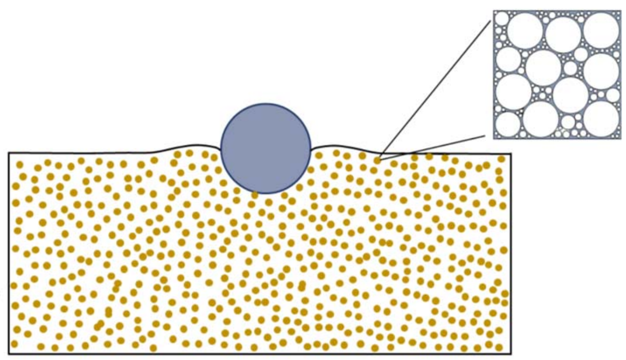
Technical Approach

3D scour model + Immersed boundary method



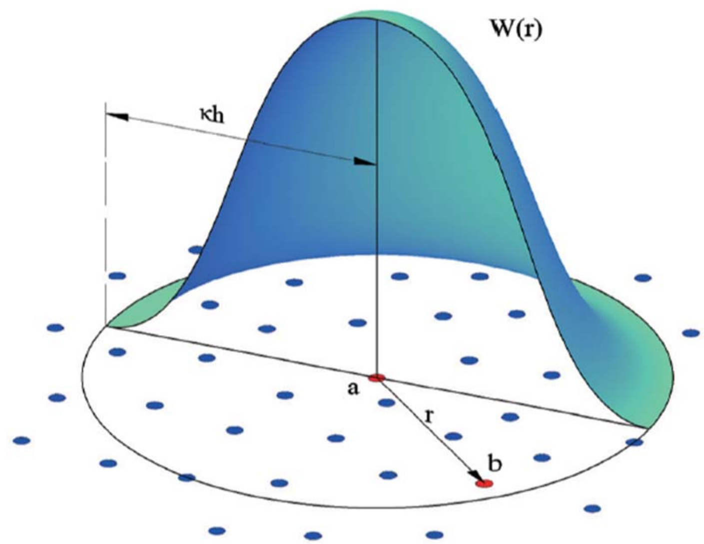
Technical Approach

Task 3: Smoothed particle hydrodynamics (SPH) granular model



Integral representation of a field function:

$$\langle f(\mathbf{x})\rangle = \int_{\Omega} f(\mathbf{x}')W(\mathbf{x}-\mathbf{x}', h)d\mathbf{x}'$$

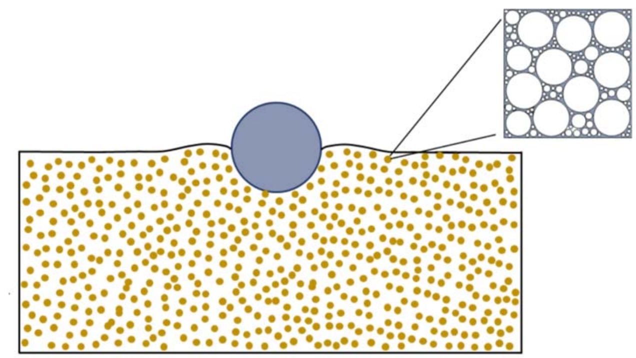


Particle approximation in SPH method

Technical Approach

Task 3: Smoothed particle hydrodynamics (SPH) granular model

To model saturated sediment, it has:
- water phase model
- sediment phase model

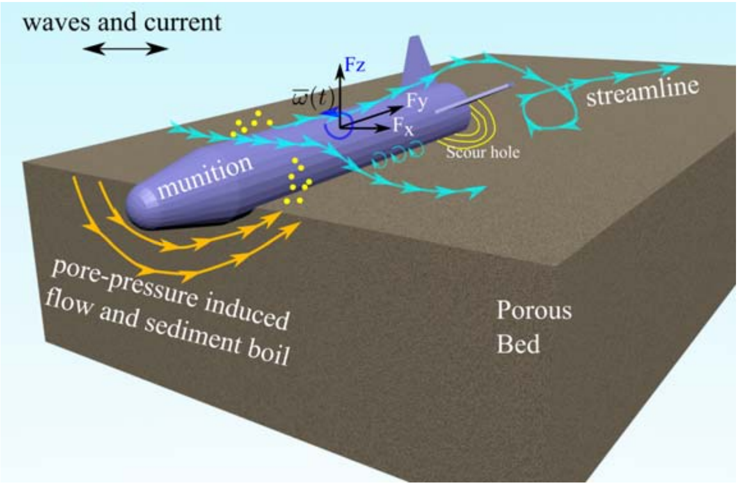


Technical Approach

Task 4: Munition motion model

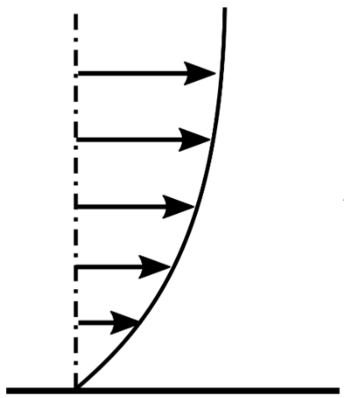
To model munition motion:

- Force and moment on munition
- 6-degree of freedom motion

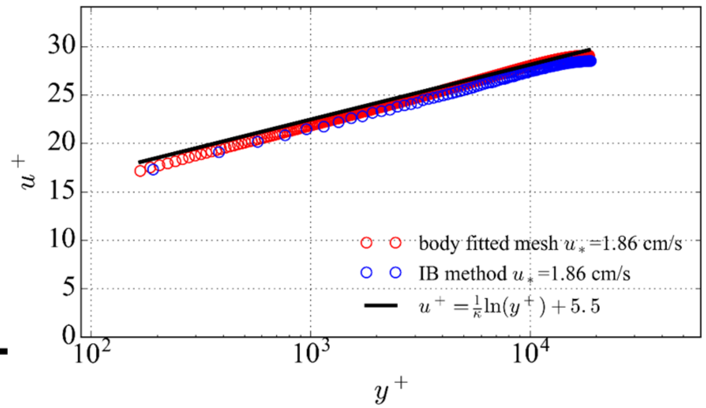


Results for Task 1 and 2

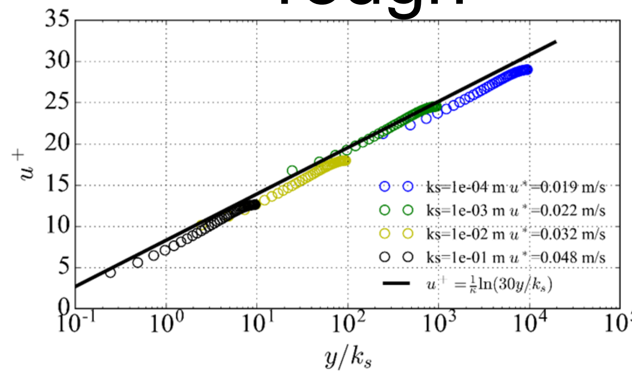
1D



smooth

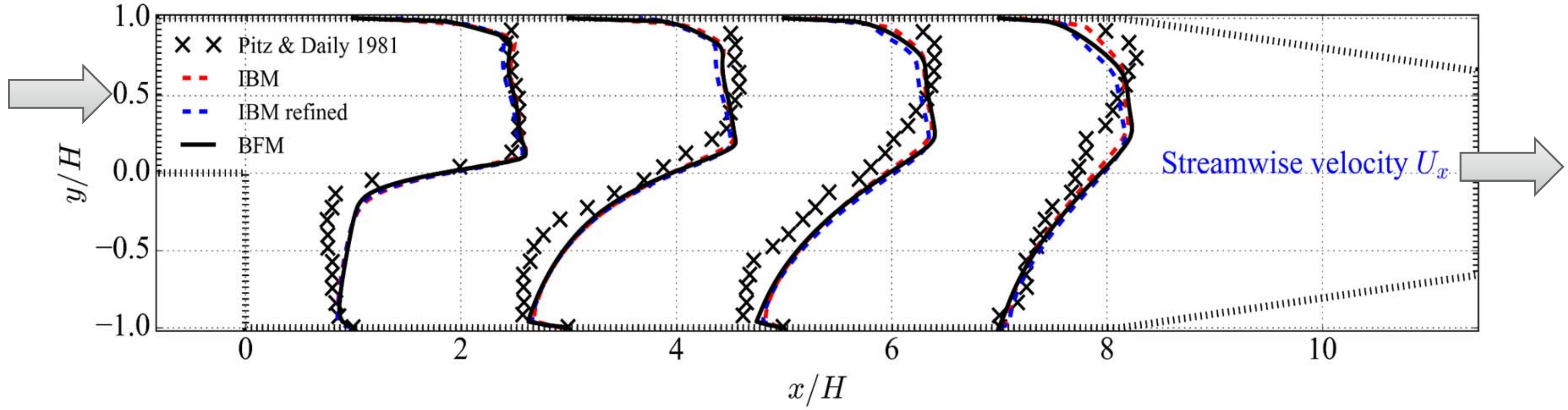


rough



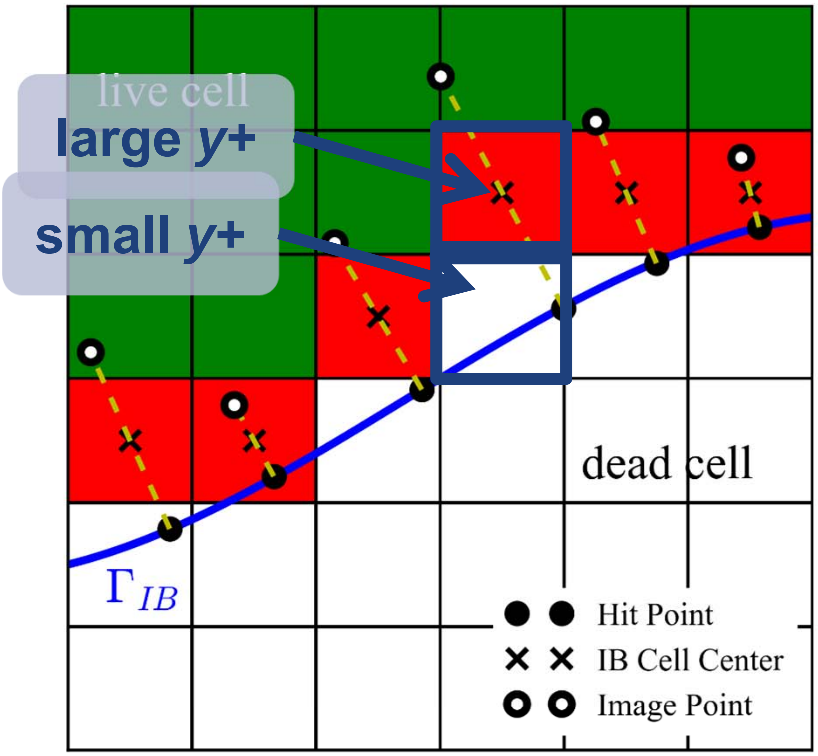
2D

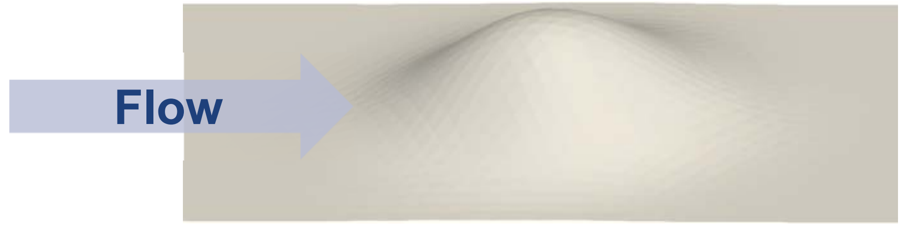
Pitz & Daily (1981)

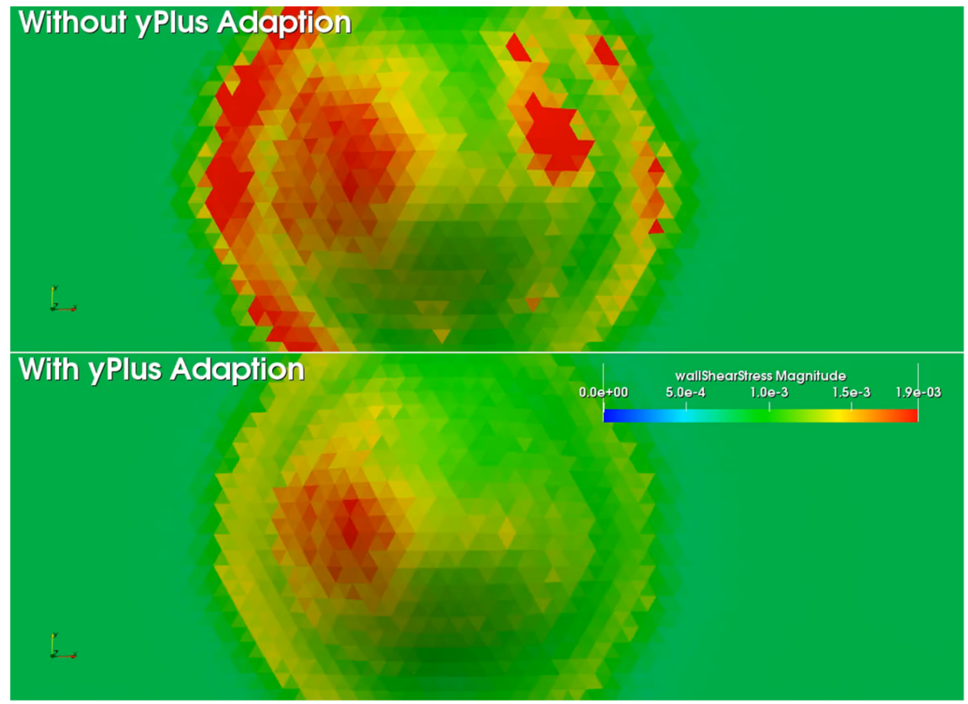


Validation of hydrodynamic part

Results for Task 1 and 2

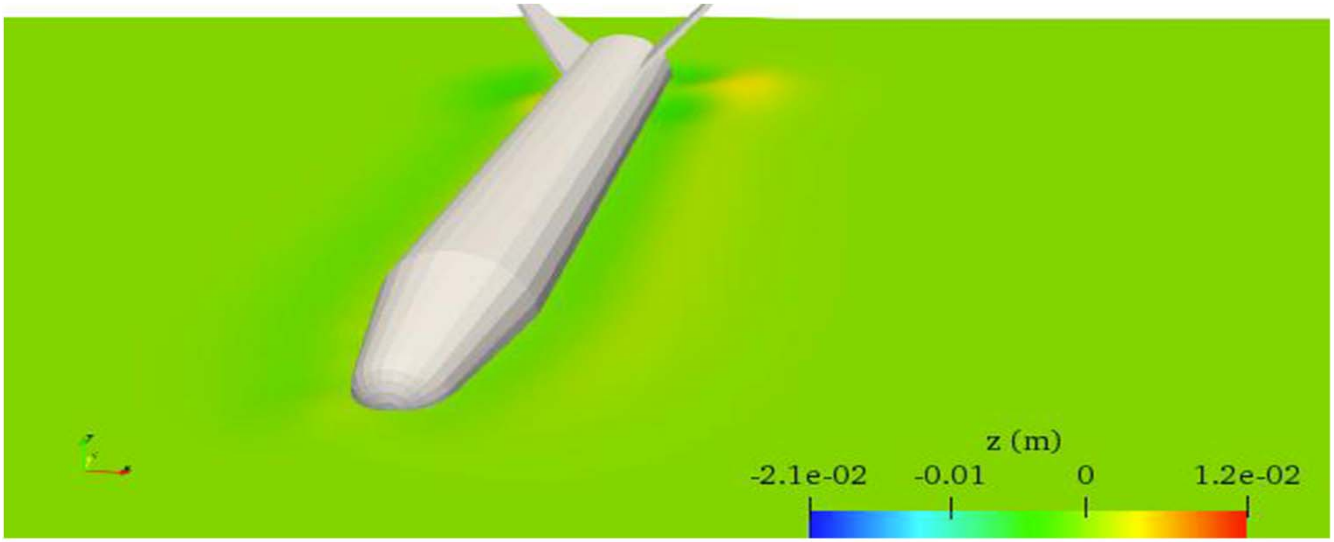


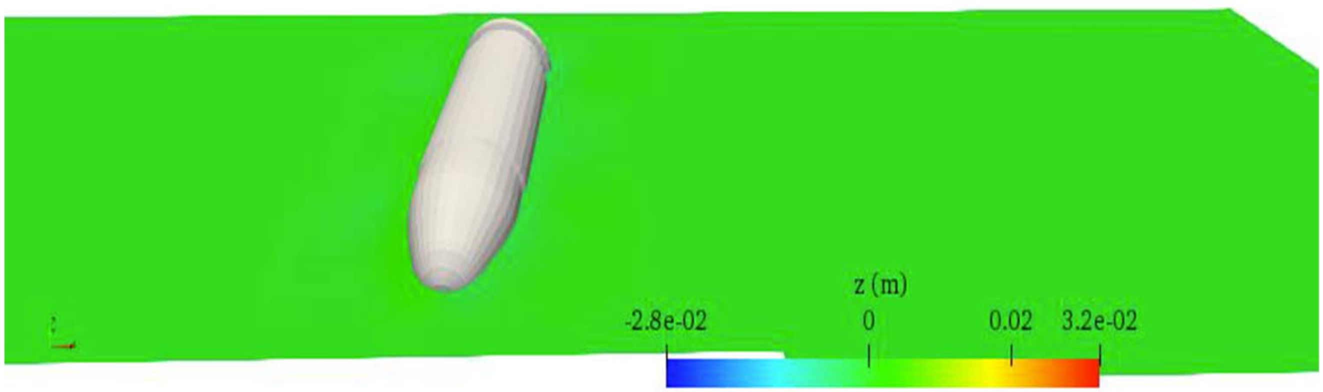




Morphodynamic part

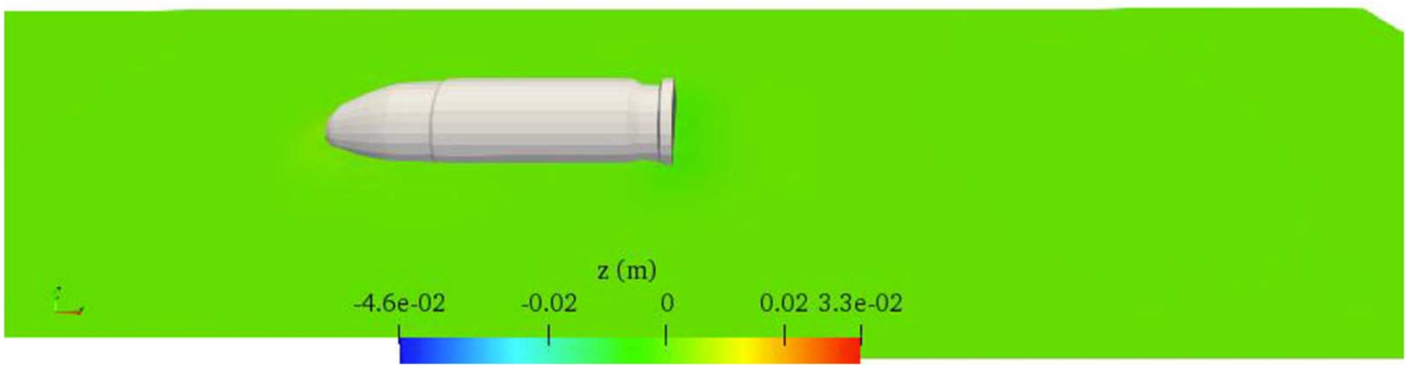
Results for Task 1 and 2

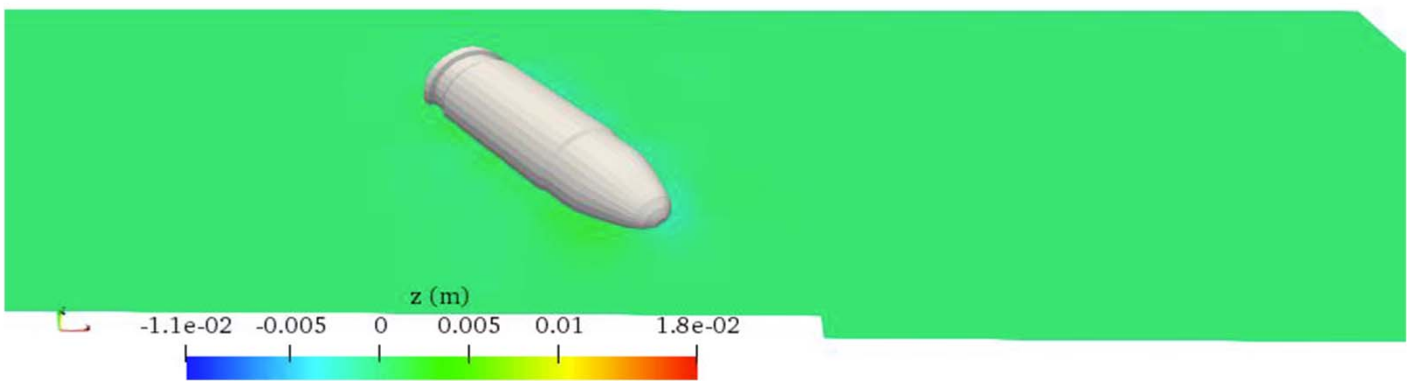




Scour around a UXO with/without fins

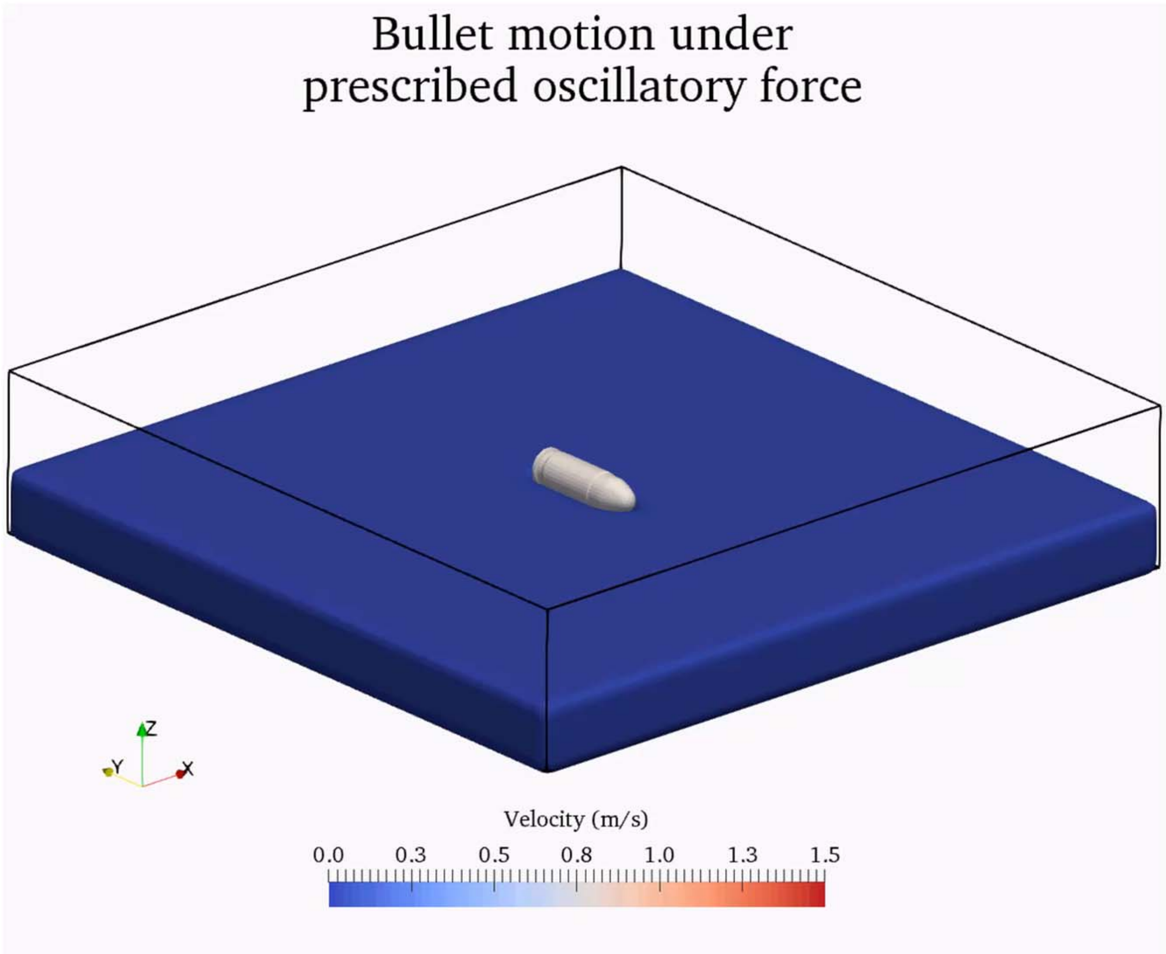
Results for Task 1 and 2





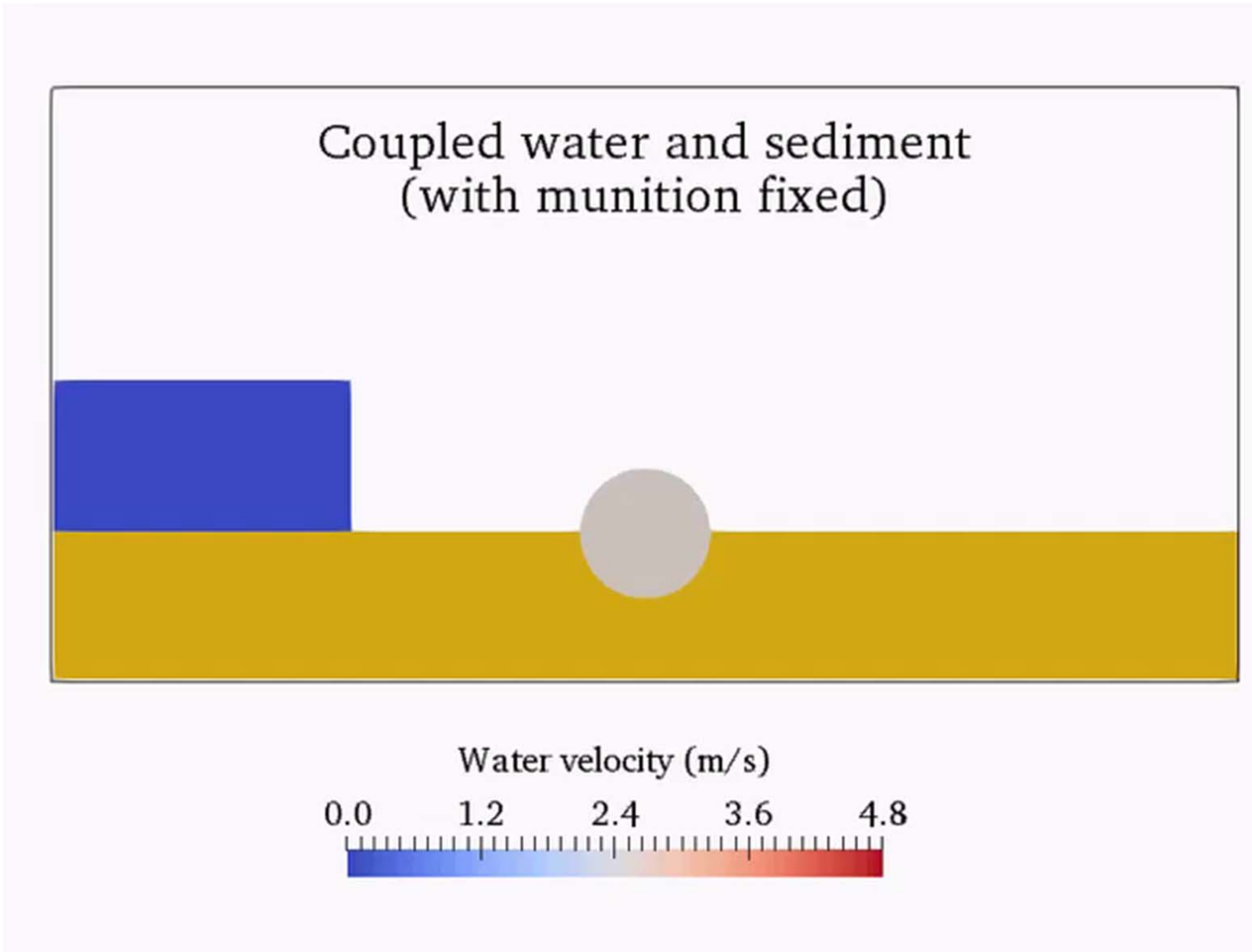
Scour around a bullet with different angles

Results for Task 3 and 4



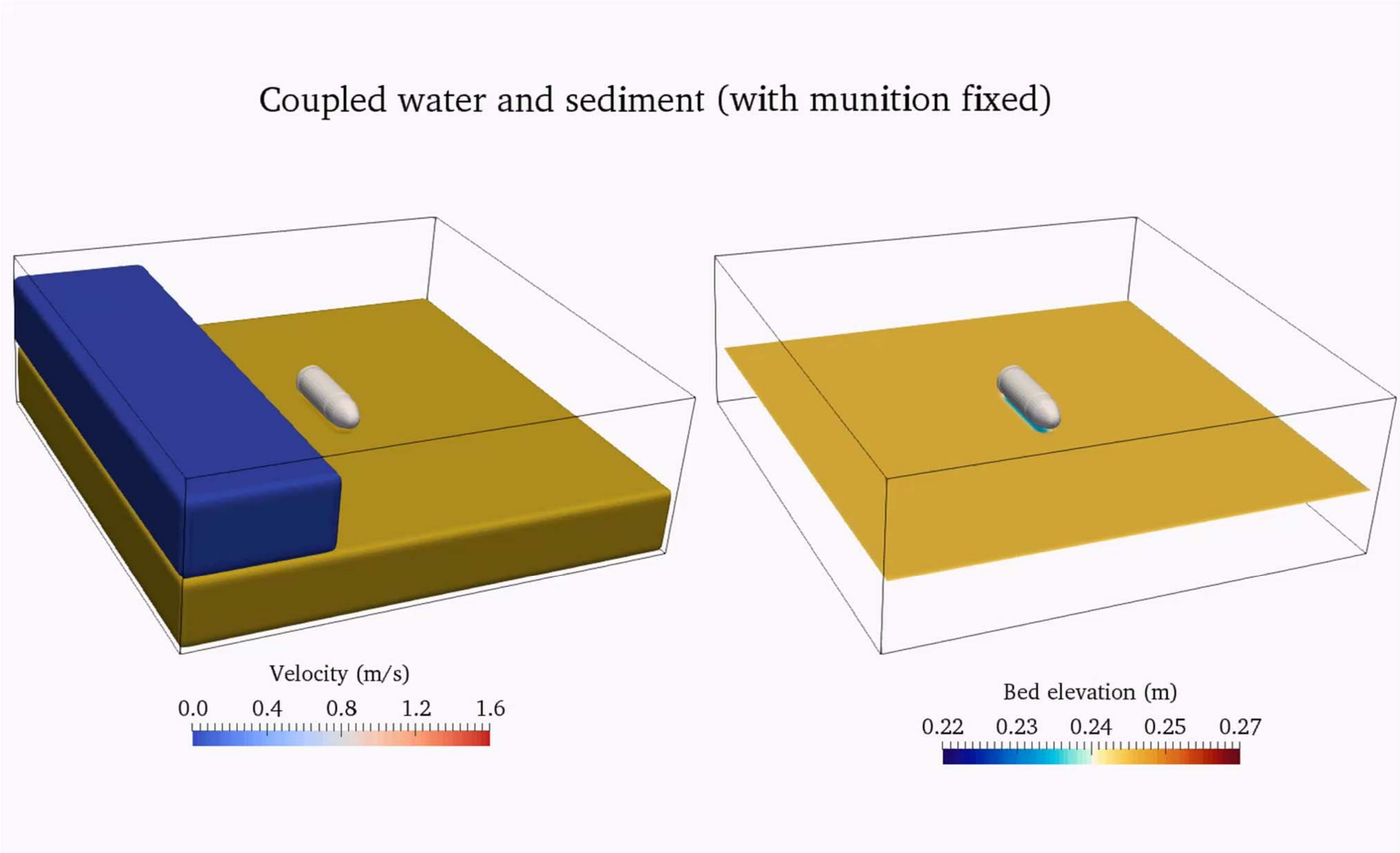
SPH model for granular material

Results for Task 3 and 4



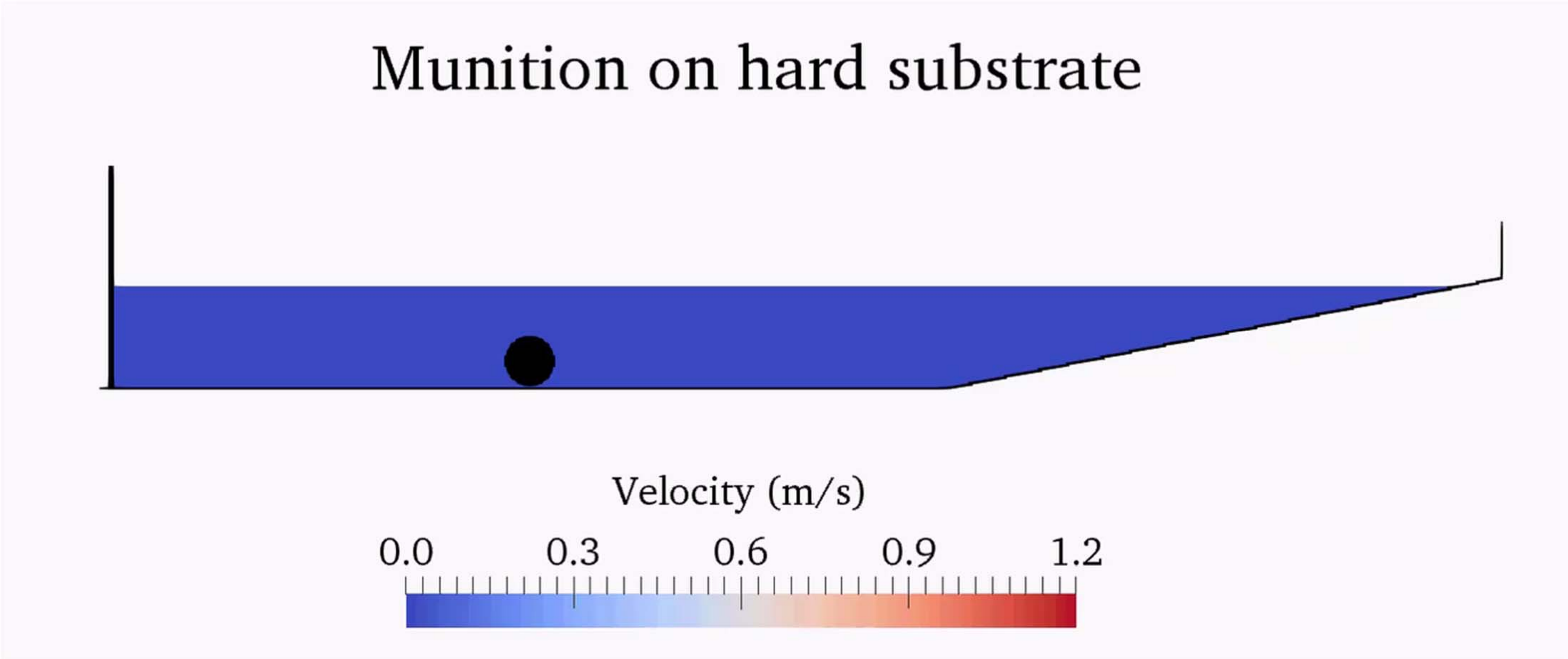
SPH model for granular material

Results for Task 3 and 4



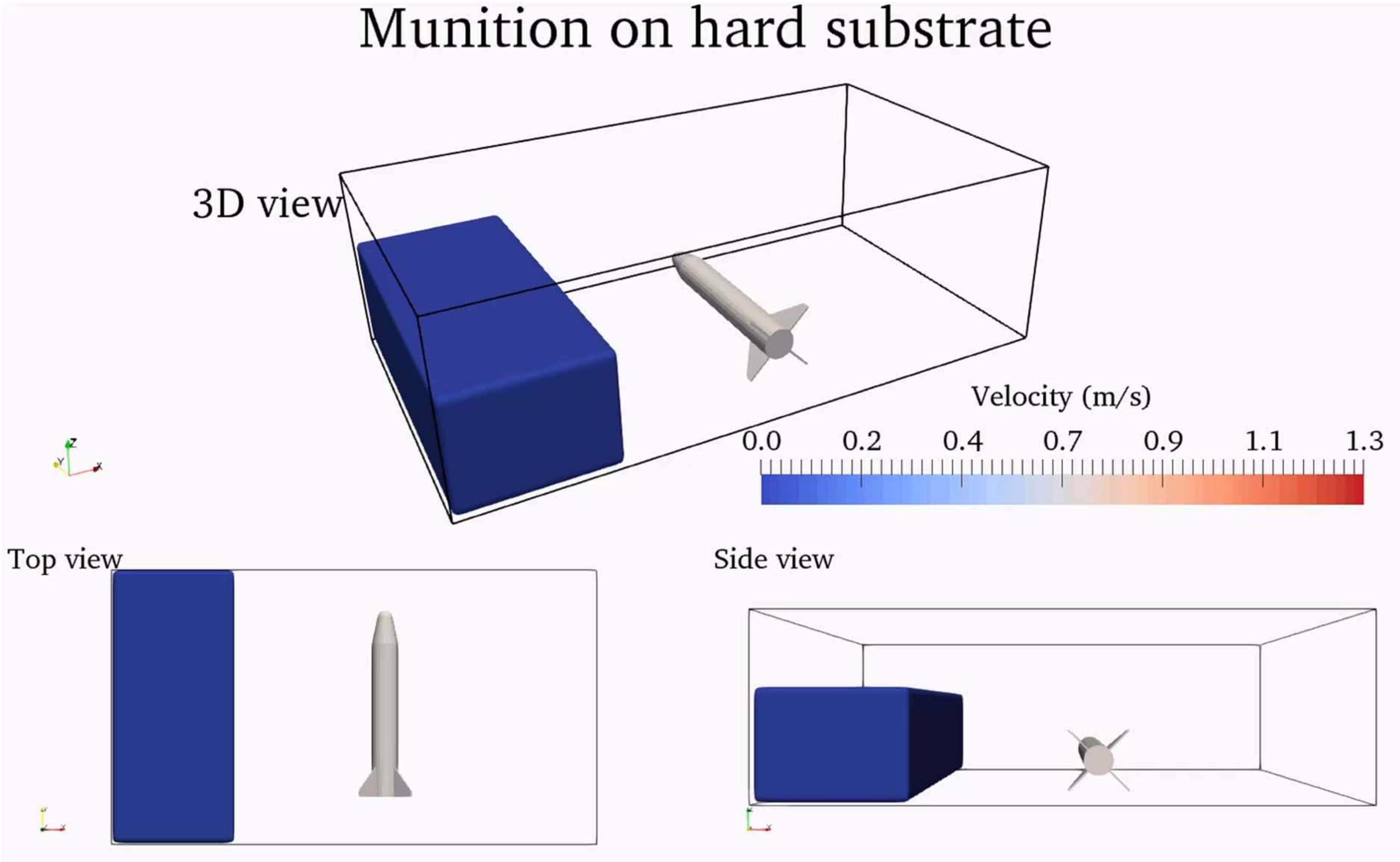
SPH model for granular material

Results for Task 3 and 4



SPH model + Munition motion

Results for Task 3 and 4



SPH model + Munition motion

Transition Plan

- No interim product yet for field use.
- Transition this research through Demonstration/Validation into field use:
  - Maybe to identify a field site where monitoring and measurement data are available.
  - Future ESTCP project possible.
- We also work with other PIs (Drs. Joe Calantoni, Blake Landry, and Marcel H. Garcia)

Issues

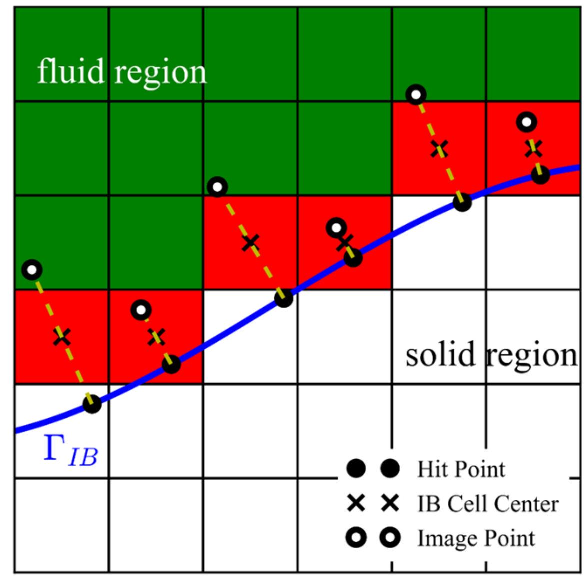
- Budget shortage
  - ♦ Only budgeted one graduate research assistant
  - ♦ Two are hired to work on the two different pieces of the comprehensive model (CFD + SPH)
  - ♦ As a result, one graduate student is not funded (she has to do something else to support herself; may slow down progress)

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

Scour model development

- Sediment bed surface is model as an immersed boundary (IB):
  - No-slip boundary condition is indirectly imposed
  - IB wall function --- important for **wall shear stress and sediment transport**
- The model is implemented in **OpenFOAM**
- Our 3D scour model has two parts:
  - Hydrodynamic part
  - Morphological part



2D schematic of IB representations:

IB cells (red filled)
live cells (green filled)
dead cell (white filled)
Immersed interface (blue curve).

Scour model development

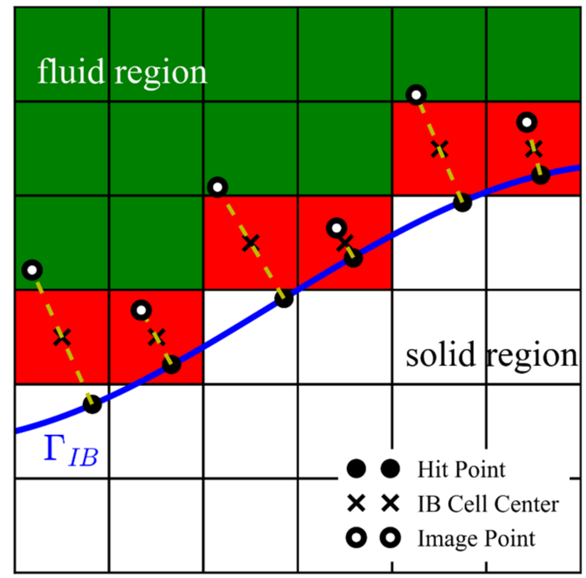
- IB wall function with k-epsilon model

$$y_{IP}^{+} = C_{\mu}^{1/4} y_{IP} k_{IP}^{2} / \nu \quad (1)$$

$$u_{*,IP} = \begin{cases} C_{\mu}^{1/4} k_{IP}^{2} & \text{if } y_{IP}^{+} > 11 \\ u_{IP} / y_{IP}^{+} & \text{if } y_{IP}^{+} \le 11 \end{cases} \quad (2)$$

- Assume

$$y_{IB}^{+} = y_{IP}^{+} \frac{y_{IB}}{y_{IP}} \quad (3)$$



ic of IB representations:

IB cells (red filled)
live cells (green filled)
dead cell (white filled)
Immersed interface (blue curve).

Scour model development

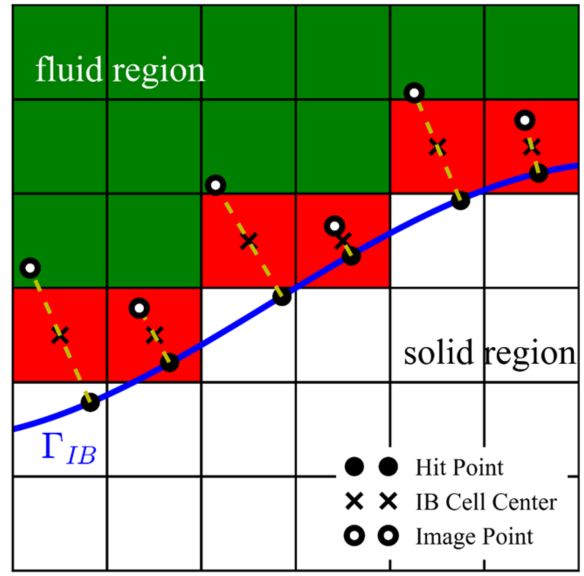
➢ Reconstruct unknowns in IB cells based on wall law

$$u_{IB} = u_{*,IB} u_{IB}^{+} = u_{*,IB} \frac{1}{\kappa} \log(E\ y_{IB}^{+}) \quad (4)$$

$$\nu_{T,IB} = \nu \left(\frac{y_{IB}^{+}}{1/\kappa \log(E\ y_{IB}^{+})} - 1 \right) \quad (5)$$

$$k_{IB} = (\nu_T + \nu) \frac{\partial u_{IB}}{\partial y} C_{\mu}^{-1/2} \quad (6)$$

$$\epsilon_{IB} = \frac{C_{\mu}^{3/4} k^{3/2}}{\kappa y_{IB}} \quad (7)$$



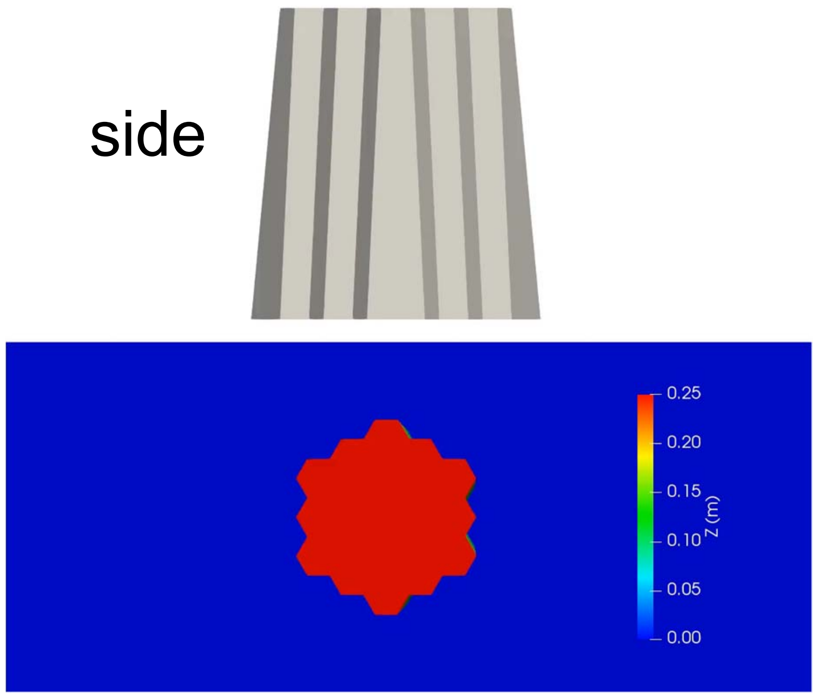
2D schematic of IB representations:

IB cells (red filled)
live cells (green filled)
dead cell (white filled)
Immersed interface (blue curve).

Scour model development

- Both bed-load and suspended load
- Sand-slide algorithm on immersed boundary

side



Basic concept of SPH

- Integral representation of a field function:

$$\langle f(\mathbf{x})\rangle = \int_\Omega f(\mathbf{x}')W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'$$

- Smoothing function should satisfy:
  - Normalization condition

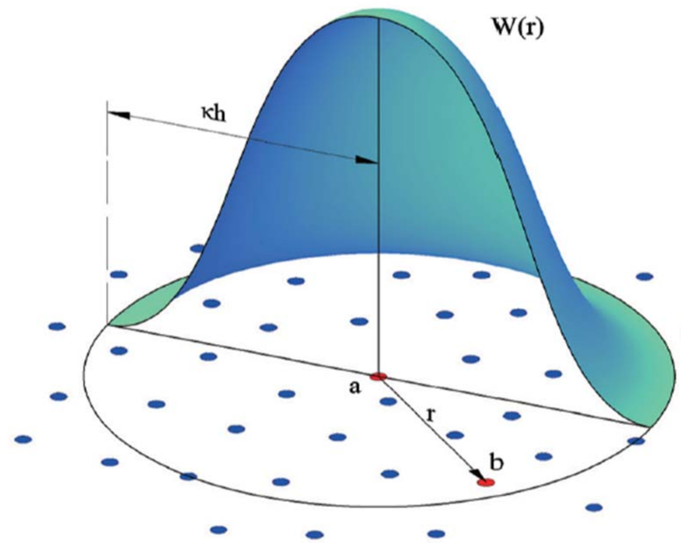
$$\int_\Omega W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}' = 1$$

  - Delta function property

$$\lim_{h\to 0} W(\mathbf{x}-\mathbf{x}',h) = \delta(\mathbf{x}-\mathbf{x}')$$

  - Compact support condition

$$W(\mathbf{x}-\mathbf{x}',h) = 0 \qquad when\ |\mathbf{x}-\mathbf{x}'| > kh$$



Particle approximation in SPH method

Liquid phase model

- Governing equations (Continuity and Momentum):

$$\frac{D\rho}{Dt} = -\rho \frac{\partial v^\alpha}{\partial x^\alpha}$$

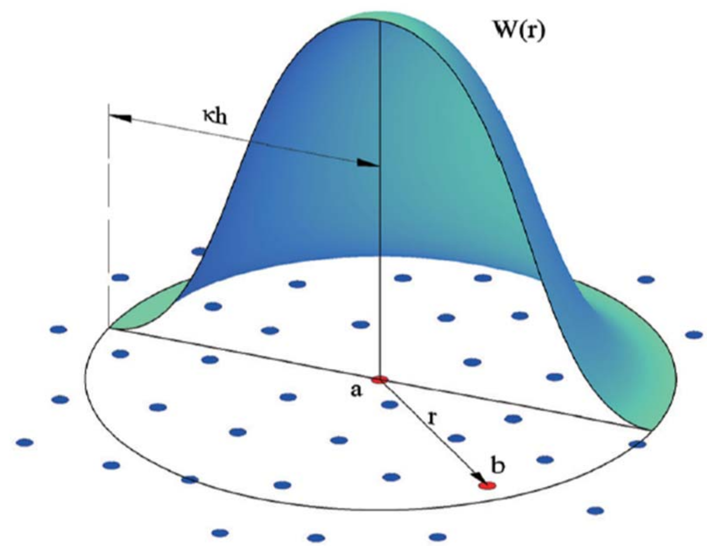
$$\frac{Dv^\alpha}{Dt} = \frac{1}{\rho}\frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta} + g^\alpha$$

- Translated into SPH form:
  - Continuity

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j (v_i^\alpha - v_j^\alpha)\frac{\partial W_{ij}}{\partial x_i^\alpha}$$

  - Momentum

$$\frac{Dv_i^\alpha}{Dt} = \sum_{j=1}^{N} \left(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_j^{\alpha\beta}}{\rho_j^2}\right)\frac{\partial W_{ij}}{\partial x_i^\beta} + g_i^\alpha$$



Particle approximation in SPH method

Sediment phase model

- Drucker-Prager (DP) yield criterion:

$$\sqrt{J_2} - |\tau_y| = 0$$

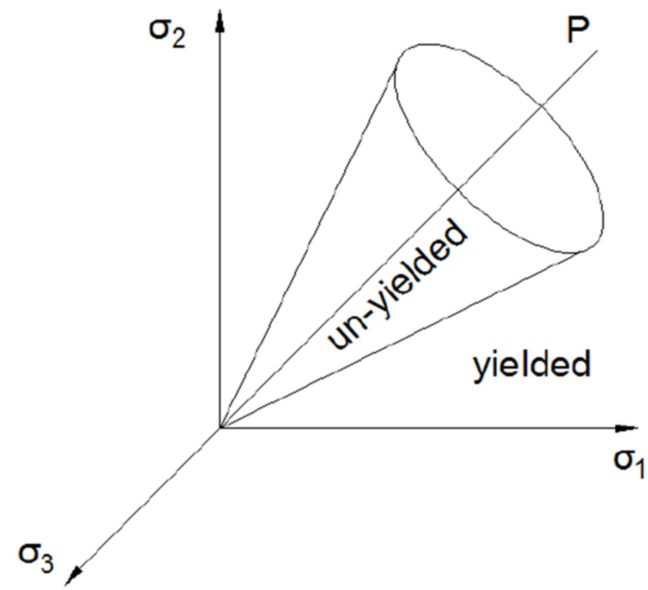
- Apply the yield criterion:

$$|\tau_y| = -\alpha \mathrm{I}_1 + \kappa$$

- Yielding occurs when:

$$-\alpha I_1 + \kappa \leq 2\mu\sqrt{II_D}$$

$$a = -\frac{2\sqrt{3}\sin(\phi)}{3-\sin(\phi)} \qquad \kappa = \frac{2\sqrt{3}\cos(\phi)}{3-\sin(\phi)}$$



Drucker-Prager (DP) yield surface in principal stress space

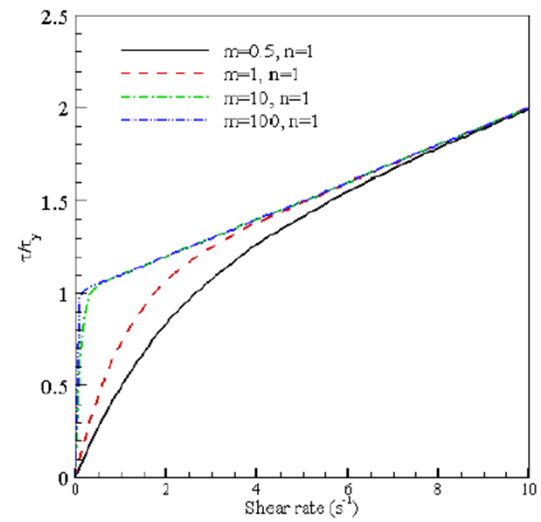
Sediment phase model

- Sediment constitutive equation:
  - Simple Bingham

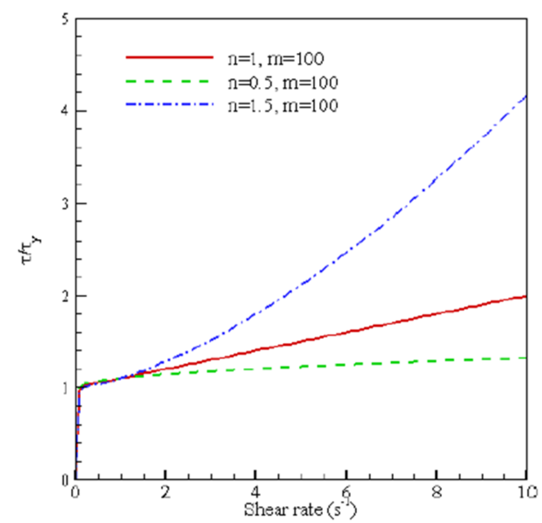
$$\phi_1 = \frac{\tau_y}{\sqrt{II_D}} + 2\mu_d, \qquad for\ \tau \geq \tau_y,$$
$$\phi_1 = 0, \qquad for\ \tau < \tau_y$$

  - Herschel-Bulkley-Papanastasiou (HBP):
    - Viscous – Plastic (m exponential growth)
    - Shear thinning or thickening (n power law)

$$\phi_1 = \frac{|\tau_y|}{\sqrt{\mathrm{II}_D}}\left[1 - e^{-m\sqrt{\mathrm{II}_D}}\right] + 2\mu|4II_D|^{\frac{n-1}{2}}$$



(a)



(b)

Publications

- N/A